4.0 IN SITU GROUNDWATER FLOW SENSORS

This section describes the in situ groundwater flow sensors and discusses their operation, data collection, and data evaluation.

4.1 DESCRIPTION OF GROUNDWATER FLOW SENSORS[1]

The groundwater flow sensors installed at CCAS were developed at Sandia National Laboratories and manufactured by HydroTechnics, both of Albuquerque, New Mexico. The flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media. The flow sensors differ from other devices to measure groundwater velocity in that they are in direct contact with the unconsolidated aquifer matrix where the flow is to be measured, thereby avoiding borehole effects. The flow sensor is a thin, cylindrical device that is permanently buried at the depth where the velocity of groundwater flow is to be measured.

The flow sensors operate on the principle that if the heat flux out of the cylinder is uniform over its surface, the temperature distribution on the surface of the cylinder will vary as a function of the direction and magnitude of groundwater flow past the cylinder. Because heat introduced into the formation by the heater is advected by flow of fluid around and past the instrument, relatively warm temperatures are sensed on the downstream side of the probe and relatively cool temperatures are detected on the upstream side (Ballard 1996). Thus, the direction and magnitude of groundwater flow are recorded as those locations in the cylinder where the temperature gradients are the highest.

Each flow sensor consists of a cylindrical heater, 30 inches long by 2 3/8 inch in diameter with an array of 30 calibrated temperature sensors on its surface. When the instrument is installed directly in contact with the unconsolidated aquifer matrix and activated, the heater warms the aquifer matrix and groundwater around the instrument to 20 to 30 ^{o}C above background temperature. The distribution of temperature on the surface of the sensor is independent of azimuth and symmetrical about the vertical midpoint of the sensor in the absence of any flow. When there is flow past the sensor, the distribution of the surface temperature is perturbed as the heat emanating from the sensor is advected by the moving fluid.

[1] All pipe diameters and lengths are listed in American Standard Engineering units. Please see page xiv for conversion factors for metric units.

The flow sensors are designed to be installed into the subsurface through the center of a hollow-stem auger flight, typically through a standard 4.25-inch-inner-diameter hollow-stem auger. Each sensor is connected to the surface by electrical cables housed in 2-inch schedule 40 PVC well casing. One electrical cable provides power for the 40-ohm electrical resistance heaters on each sensor. Seventy watts of power input are required to operate a 57-volt direct current (DC) power supply at 1.4 amps. The thermistors within the sensors have a normal resistance of 1 megaohm at 25 ^{o}C, about 2.5 megaohm at 10 ^{o}C, and about 125 killiohm at 70 ^{o}C. Table 4 provides a summary of the specifications for the flow sensors.

Data loggers collect and store data as millivolt readings derived from the thermistors. The data logger can be programmed to collect data as frequently as once every minute. Once data are collected, they can be manually downloaded in the field using a laptop computer or they can be acquired remotely through a modem. The data can be interpreted via HydroTechnics' proprietary software, HTFLOW© (HydroTechnics 1997). The software accepts the raw millivolt data and converts them into temperature data; temperature data can then be manipulated and simulated to calculate velocities of groundwater flow using an inverse technique. The resulting output includes horizontal and vertical groundwater velocity vectors and an azimuth for horizontal direction of flow.

4.2 INSTALLATION OF GROUNDWATER FLOW SENSORS

Seven flow sensors were installed in the deep and shallow aquifer zones in two separate clusters. The flow sensors were installed from June 26 to June 28, 2000; data collection and data downloading began by July 1, 2000. Specifications for installation of the flow sensors are provided in Table 5.

Locations of the sensors in the deep and shallow aquifer zones relative to the GCW are shown in Figure 6. Four flow sensors (D-series) were installed southeast of the GCW, and three flow sensors (C-series) were installed southwest of the GCW. The radial distances of the flow sensors from the GCW were selected based on modeled predictions of the extent of the circulation cell created by the GCW. The modeling results were also used to predict the velocity of groundwater flow in the area that surrounds the GCW. A general criterion was established to define the area of the GCW circulation cell where changes in the velocity of groundwater flow either horizontal, vertical, or both of more than 0.1 ft/day occur. Based on this criterion and on the results of the GCW modeling, two of the flow sensor clusters (C01/C02 and D01/D02) were installed within the predicted radius of the circulation cell, 7.5 feet from the GCW. The other two flow sensor clusters (C03/C04 and D03) were installed at 13 to 15 feet from the GCW.

The depths of the flow sensors were selected in reference to the upper and lower screened intervals of the GCW. The upper screen of the GCW was installed from 5 to 10 feet bgs, and the lower screen of the GCW was installed from 20 to 30 feet bgs. When the flow sensors were installed, the water table was approximately 8 feet bgs, based on a water level measurement in piezometer 3PZS made on July 7, 2000 (Parsons 2000). The shallow flow sensors were installed at depths so that the top of each sensor was approximately 8.5 feet bgs, or about 0.5 foot below the static water table. The deep flow sensors were installed at depths so that the top of the sensor was approximately 17 to 19 feet bgs. Based on recommendations by HydroTechnics, the deep sensors were installed first, followed by the shallow sensors. This method allowed the formation time to settle around the deep sensors before drilling was resumed in their immediate vicinity.

When the soil borings were advanced for flow sensor installation, soil samples were collected at changes in lithology or at 5-foot intervals using a 24-inch-long, split-spoon sampler. The soil samples were used to assess subsurface conditions and for lithologic logging. Soil samples and cuttings were logged using the Unified Soil Classification System. In addition, the bottom 4 feet of each boring was continuously sampled to ensure that the 30-inch long sensors would be positioned in a relatively homogenous lithologic section of the soil column. As such, the depths proposed for the sensors were adjusted based on the subsurface conditions encountered during installation to ensure a homogenous lithologic section in the vicinity of the flow sensor.

4.3 OPERATION OF GROUNDWATER FLOW SENSORS

The flow sensors were connected to a control panel to provide electrical power for their heaters and to store outputs in a data logger. Two Campbell Scientific CR-10X data loggers were used to record sensor data and were connected to a modem for remote data access. One data logger was dedicated to the four cross-gradient sensors, and the other data logger was dedicated to the three downgradient sensors. Starting on July 1, 2000, the data loggers recorded data from each sensor every 30 minutes for the 6-month evaluation period. The data from the flow sensors were collected at 2-minute intervals during the aquifer testing period from September 11 to September 20, 2000.

Data from the flow sensors were being collected and stored as millivolt readings, derived from the thermistors that cover the sensors. Failure of a power strip at the beginning of September 2000 (potentially the result of lightning strikes) caused all of the flow sensors to power down. The failure was discovered and the power strip was replaced; the flow sensors were restarted on September 11, 2000.

Based on the memory capacity of the data loggers and the proposed frequency of data collection, each data logger rewrites over old data about every 2 months. Each data logger was downloaded remotely every 30 days using a modem to ensure that no data would be lost. This schedule allowed approximately 30 days to collect data manually in the event that remote access capabilities were lost. The raw sensor data was processed using HTFLOW© software. A copy of the HTFLOW© software manual was included as Appendix A in the TEP/QAPP (Tetra Tech 2000).

4.4 LIMITATIONS OF FLOW SENSOR DATA AND DATA MANIPULATION

The process of simulating and manipulating data from the flow sensors yields a three-dimensional vector for velocity of groundwater flow, which is then converted to the horizontal Darcy flow rate, vertical Darcy flow rate, and the azimuthal direction of groundwater flow. The limitations of data manipulation are discussed in the following sections.

4.4.1 Flow Velocity Simulation

Vectors for the velocity of groundwater flow were simulated using HTFLOW©, which employs an inversion process to match theoretical curves with the observed temperature data. When the observed temperature data are discontinuous or exceed the upper bounds of the recommended velocities, the simulation becomes unstable and difficult to converge and could result in inversion errors. In general, small, abrupt temperature changes can be simulated by varying the time-steps (averaging the data to smooth the curve).

During the study period, some flow sensors recorded huge changes in temperature gradient as a result of exposure to ground water flows in excess of the specified 2.0ft/day upper limit. These high ground water flows induce large inversion errors and an unreliable calculated velocity. In such cases, velocity data were omitted represented as corresponding data gaps in the hydrographs. For example, deep flow sensor D01 showed several gaps in velocity data during the aquifer hydraulic testing period. However, the raw millivolt data collected in these circumstances provided a useful, if qualitative, window into how quickly flow vectors changed.

4.4.2 Placement of Flow Sensors in Relation to Direction of Groundwater Flow

The flow sensors were installed based on distance from the GCW and relative to the expected natural direction of groundwater flow toward the southwest. Based on this assumption, cross gradient (southeast) and downgradient (southwest) clusters of flow sensors were installed. However, because of the probable presence of a groundwater flow divide near the GCW, direction of groundwater flow is more variable. As a result, the relationship of the flow sensors to the horizontal hydraulic gradient is most likely transient. Therefore, the flow sensors and clusters are referred to as “southeast” and “southwest,” rather than “cross gradient” and “downgradient” for this evaluation.

4.4.3 Depth of Shallow Flow Sensors with Respect to Water Table

The manufacturer’s recommended installation depth requires a minimum of 5 feet of saturated aquifer material between the top of the flow sensor and the water table. If the flow sensor is too near the unsaturated zone, which tends to be higher in temperature than the underlying groundwater, then the existing temperature gradient will incorrectly be interpreted by the sensor as upward flow. These superposed vectors can be accounted for and corrected using the programs’ vector subtraction feature. To evaluate the flow in the upper screened interval, it was decided in the field to install the shallow sensors at a depth of approximately 1 foot below the existing groundwater surface (approximately 8 feet below ground surface) to allow the sensor to be placed at a depth similar to the upper screened interval of the GCW. The limited water column above the sensors may have impaired the sensor’s performance. However, it was suspected that deeper placement of the flow sensors would compromise the ability to evaluate GCW performance in the shallow aquifer zone.

4.4.4 Accuracy and Precision of Flow Sensor Data

Past studies conducted by independent parties have shown that the flow sensors accurately record precise flow velocity data when directly compared to piezometric analysis in fluctuating flow environments such as occur in natural ground water/surface water interactions as well as pump test of many varieties. Though the probes routinely and accurately record fluctuations in flow velocities, flow velocities higher than 2 ft/day have higher interpretation errors. This upper limit is dictated by the sensor geometry and the heat flow equation central to the algorithm. The algorithm used by the sensor to calculate a flow vector requires the last collected data point; if that last data point is outside the upper specified limit, it will calculate the next data point but yield an incorrect velocity. In addition, rapid oscillations in flow velocities, as might be experienced by turning a nearby pump on and off very quickly, may yield ambiguous data. Some measure of equilibrium must be attained between changes in velocities for any one velocity to be calculated faithfully.

4.4.5 Physical Reliability of Flow Sensors

Each flow sensor consists of a rod of low thermal conductivity surrounded by a thin flex circuit heater, an array of 30 temperature thermistors, and a waterproof jacket constructed from high-density plastic and PVC. The estimated life of the flow sensors is 1 to 2 years (Ballard 1996) though many have lasted much longer.

The flow sensors are capable of measuring groundwater flow velocities in the range of approximately 5 X 10^{-6} to 1 X 10^{-3} centimeters per second (cm/s) (0.014 to 2.8 feet per day) (Ballard 1996). Higher flow rates than were anticipated near the GCW exceeded the capability of the instruments. For this evaluation, flow velocities greater than 3 feet per day were considered less reliable.